EARLY ELECTROSTATIC PROBE RESULTS FROM EXPLORER XXII

by

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ABSTRACT 22221

The electrostatic probe experiment on Explorer XXII has permitted the concentration and temperature of the electrons at 1000 kilometers to be observed on a global scale. The major features of the ionosphere at this altitude are a maximum concentration at the magnetic equator in the daytime which gives way at night to a pair of maxima at 35° north and south. The electron temperature exhibits large variation from day to night at latitudes below 45° but remains high all night at higher latitudes. This behavior is consistent with the heating of the protonosphere by escaping photoelectrons in the daytime, and cooling by thermal conduction to the lower atmosphere both day and night.

Author

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INTRODUCTION

On October 9, 1964, Explorer XXII, the ionosphere beacon satellite,[1,2] was launched into an 80° inclination direct orbit which is nearly circular at an altitude of 1000 kilometers. The primary mission of the satellite is to permit radio propagation studies of the ionosphere on a global scale. The beacon experiment, radiating at 20, 40 and 41 megacycles, permits determination of the total electron content in the region between the satellite and an observing station on the ground. Knowledge of the electron density (N_e) at the satellite is very useful in the interpretation of beacon data, and for this reason two cylindrical electrostatic probes are employed to permit direct "in situ" measurements of the local plasma. It is the purpose of this paper to describe the probe experiment, report some of the early results, and suggest their possible implications.

THE EXPERIMENT

Figure 1 shows the mounting position of the probes and the electrical system employed. The satellite is stabilized by a passive magnetic system which

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causes the spin axis to remain aligned with the local geomagnetic field, somewhat like the needle of a compass. Thus, one end of the satellite always points generally northward and the other end points southward. To insure undisturbed measurements when the satellite is moving either north or south, one sensor was mounted on each end of the satellite as shown.

The experiment is essentially identical to that employed on the Explorer XVII satellite[3] and several rocket flights.[4] In this application, a 2 cps sawtooth voltage (−3v to +5v) is applied in series with either of two independent linear current detectors which are in turn connected alternately to each of the cylindrical probes. The sensor consists of a 5-inch guard electrode and a 9-inch collector of 0.022 inch diameter. The guard prevents the collection of current in the region immediately adjacent to the spacecraft, and therefore avoids any possible related disturbance of the measurements. The collector dimensions are such that the probe operates in an orbital-motion-limited mode in which the simple Langmuir probe equations for a cylinder are applicable.[5]

When the collector is driven negative with respect to the plasma such that it repels essentially all of the thermal electrons, it is said to be <u>ion saturated</u>, and this current is the reference level from which all electron currents are measured.

The slope of the ion saturation region of a cylindrical probe depends primarily on the ion mass, and when the more sensitive current detector is employed this slope becomes measurable. Therefore the experiment is expected to yield measurements of the mean ion mass which will be reported in a later communication.

When the probe is driven positive with respect to the plasma such that it attracts electrons, it is said to be electron saturated, and the saturation equation applies[4]

$$I_e = \frac{A N_e e}{\pi} (2 eV/m_e)^{1/2}, \quad |eV/kT_e| >> 1 \tag{1}$$

where

I_e	is the electron current,
A,	the probe area,
N_e,	the electron concentration
e,	the electron charge,
k,	the Boltzmann constant,
T_e,	the electron temperature,
m_e,	the electron mass and
V,	the potential of the probe relative to plasma.

Equation (1) is the primary means by which the electron concentration, N_e, is derived from volt-ampere characteristics.

Between the ion and electron saturation regions lies the electron retardation region which is employed for the measurement of electron temperature (T_e). In this region I_e is given by

$$I_e = A N_e e (kT_e/2\pi m_e)^{1/2} \exp (eV/kT_e), \quad V < 0 \tag{2}$$

and T_e is given by

$$T_e = -\frac{e}{k} \frac{dV}{d(\ln I_e)} \tag{3}$$

Figure 2 is a photograph of a one-second segment of telemetry record which shows a pair of volt-ampere curves measured at moderate temperature and concentration. The plasma potential (V_p), from which the probe potential is measured, is identified as the inflection point of the curve. At the far left of each curve is the ion saturation region which establishes the reference level from which I_e is measured. Immediately to the left of V_p is the exponential electron retardation region from which T_e is derived. To the right is the electron saturation region which permits N_e to be measured.

THE RESULTS

At the time of this writing N_e and T_e have been derived for about 600 passes of Explorer XXII which occurred between October 10, 1964 and January 7, 1965. These data represent a wide range of latitude, longitude and local time and are generally descriptive of the ionosphere at an altitude of approximately 1000 kilometers, in northern winter.

The polar orbit, and its near circularity, makes the latitudinal structure particularly evident in the resulting measurements. For this reason we have plotted the data as a function of geomagnetic latitude. The behavior of the ionosphere with respect to other variables then appears largely as differences in the latitudinal structure. To minimize the effects of local time, we have plotted only the data corresponding to the relatively stable periods following local noon and midnight.

Actual Data Points

Figures 3 and 4 show the N_e and T_e data points taken at 10° increments of latitude and at all longitudes for the period 0000–0330 hours in November and

December of 1964. The individual points from a particular pass are joined by lines to approximate the instantaneous latitudinal structure existing during the pass and to identify the points as belonging to particular passes. The long and short dashes represent data from the stations along the 75th meridian (50°W–100°W), and only at these longitudes was it possible to obtain complete pole to pole coverage. The short dashed lines represent Woomera and some of the College passes (110°E–150°E), and the solid lines represent Johannesburg and Winkfield passes (50°E–50°W). Finally, the long dashes represent data from the western U.S. and Canada recorded at Mojave and College (100°W–130°W). The ionospheric N_e structure in this range of longitudes was sufficiently different from that of the 75th meridian to warrant plotting it separately. It should be stressed that this particular means of sorting the data by longitude arises not so much from the characteristics of the ionosphere but more from the geographic distribution of the various STADAN stations which recorded the data. Indeed most of the spread in N_e within each of the stated ranges remains longitudinal in origin. For at least one pass (labelled D), deviations have been correlated with high values of the 3-hour magnetic index a_p. In this case, the disturbance was associated with an enhancement of N_e in the equatorial region.

Latitudinal Variations

Figures 5 thru 8 summarize the gross latitudinal structure of the ionosphere both day and night at the selected longitudes. These graphs generally outline the extremes of N_e and T_e found in the given longitude ranges and are intended primarily to convey the predominant features of the ionosphere at 1000 ±100 km during this period.

At midday (Figure 5), N_e exhibits a strong maximum at the magnetic equator, a result which is consistent with the Alouette topside sounder data (Lockwood and Nelms, 1964).[6] A general decrease in N_e with increasing latitude extends to a minimum at 60°N and S latitude where N_e is about one third its equatorial value. At night (Figure 7), the equatorial maximum has given way to a pair of mid-latitude maxima at 35°N and 35°S. The value of N_e at the equatorial trough is about one half of that at the maximum. This is not unlike the pattern shown by the Ariel satellite measurement of N_e for this altitude during northern summer of 1962 (Sayers, 1964).[7] These may therefore be permanent features of the ionosphere.

At higher latitudes an extraordinarily steep gradient reduces the concentration by nearly two orders of magnitude in less than 20° of latitude. The resulting minimum at 60° North, evident also in Aloutte data has been called the auroral trough (Muldrew, 1965: private communication). This also seems to be a permanent feature of the ionosphere, but is most discernible at night. The fact that the trough occurs at a magnetic latitude of 60° leads one to suspect that this is caused by the same phenomena which produce the "knee whistlers" observed by Carpenter (1964)[8] near magnetic invariant L = 4. The polar cliff, an enhancement north of the auroral trough noted by Muldrew does not seem to be present at all longitudes (See Figure 7).

Local Time Behavior of T_e and N_e

Although data for a half rotation of the orbit plane (3 months) are not yet analyzed for all stations, it has been possible to analyze enough data to outline the diurnal behavior of the ionosphere at a few locations. Figure 9 shows the diurnal variation of T_e at mid-latitudes near the 75th meridian. Most of the spread in the data arises from the wide longitude and latitude window employed to obtain sufficient point density.

DISCUSSION OF RESULTS

The explorer XXII measurements reveal a degree of symmetry about the magnetic equator which permits little doubt that the protonosphere is strongly controlled by the geomagnetic field, an effect which was evident also in the satellite data from Ariel (Boyd and Raitt, 1965)[9] (Sayers, 1964),[7] Alouette (Lockwood and Nelms, 1964),[6] and Explorer XVII (Brace, et al, 1964).[3] Figure 10 summarizes the global distribution of electrons in the lower protonosphere and shows how N_e varied from day to night during a three week period in November and December, and Figure 11 shows the simultaneous variations of T_e. These results are averages over all longitudes. Figure 12, which shows the path of Explorer XXII through the geomagnetic field, should be useful in visualizing the sampling geometry with respect to the magnetic field and the protonosphere.

Hanson and Ortenburger (1961)[10] have shown that 0^+ ions at the lower boundary of the protonosphere form a proton diffusion barrier which prevents substantial diurnal variations in the total electron content along a field line. This barrier permits the protonosphere to be considered a charge conserved system, at least over periods of the order of days. Within any field tube of this charge conserved system one can expect to find continuous redistribution of charge in response to the changing electron and ion temperatures, the greatest changes being diurnal in nature. Evans (1965)[11] has invoked this mechanism to explain the evening enhancement of $f_0 F_2$ in the mid-latitude ionosphere. It now appears that the major features of the global diurnal variations of N_e and T_e reported here are also consistent with temperature-induced charge redistributions.

Hanson[12] (1963) suggested that the protonosphere is heated in the daytime by field aligned photoelectrons which escape the F region. In response to this heating, the ambient electrons and protons attempt to adjust to a new equilibrium distribution along the field lines. As a result the ionization is transported upward from each hemisphere and forms the equatorial maximum of N_e which has been observed at 1000 kilometers. The equatorial maximum can be assumed to be a feature of the protonosphere at higher altitudes as well. Indeed, whistler studies (Carpenter,[8] 1963), ion mass spectrometer data (Taylor, et al 1965),[13] and ion trap results (Gringauz, et al, 1965)[14] show that N_e decreases only very gradually with altitude above the equator out to altitudes of 15,000–20,000 kilometers ($L \simeq 3$-4). These workers have also shown that, near $L = 4$, the N_e profile exhibits a "knee" in which the concentration decreases by about an order of magnitude in a few thousand kilometers.

At night, the protonosphere heat source is removed and the hot electrons cool by electron heat conduction along the field lines downward to the F_2 region where the electrons and ions can lose energy by collisions with the neutral particles which are abundant there. However, as Geisler and Bowhill (1965)[15] have commented, the rate of heat conduction itself depends strongly upon T_e, which makes the cooling process self-limiting. As a result, the temperature of the protonosphere can only decrease significantly where the heat reservoir (the electron content along the field line) is small enough. Apparently, the reservoir is sufficiently small where $L < 2$, because T_e is observed to decrease markedly at night only at the corresponding low latitudes. The resulting downward and poleward redistribution of charge at night in the region $L < 2$ may produce the maxima of N_e observed to develop near $35°$ latitude ($L \approx 1.7$).

The heat content of the protonosphere at higher L values ($L > 2$) apparently cannot be conducted away in a single night, since T_e is observed to remain high all night at the corresponding higher latitudes. Therefore, the proton concentration at higher L values ($2 < L < 4$) would not be expected to exhibit large diurnal variations. The measurements of N_e reported here, however, reveal large diurnal variations at 1000 kilometers at high latitudes. It follows that these variations must not be protonospheric in origin, but rather reflect the diurnal variation in the concentrations of the heavier ions (0^+ and H_e^+) which undoubtedly are the major constituents there, at least during the day. This conclusion is consistent with mean ion mass values derived from the ion current slopes, as mentioned earlier. Furthermore, a similar latitudinal dependence of composition has been reported for an earlier period from Ariel data (Bowen, et al 1964) and from Alouette data (Barrington, et al, 1965).

A note of qualification regarding the reference to these as "protonosphere" measurements is in order. The observed latitudinal variation of composition implies a latitude control of the altitude of the ionosphere-protonosphere boundary. Since the boundary can be expected to ride up and down with the diurnal expansion of the 0^+ population, its altitude must depend upon local time as well. It appears that the Explorer XXII measurements near the equator were clearly made within the protonosphere, and that the polar daytime measurements were clearly below the protonosphere and therefore cannot be regarded as "protonosphere" measurements.

Analysis of data at other local times and for later orbit plane precession cycles is in process, and these results are expected to provide detailed resolution of the dynamic response of the protonosphere throughout the diurnal cycle and should provide the basis for testing quantitative theories of the diurnal redistribution of ionization.

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LIST OF FIGURES

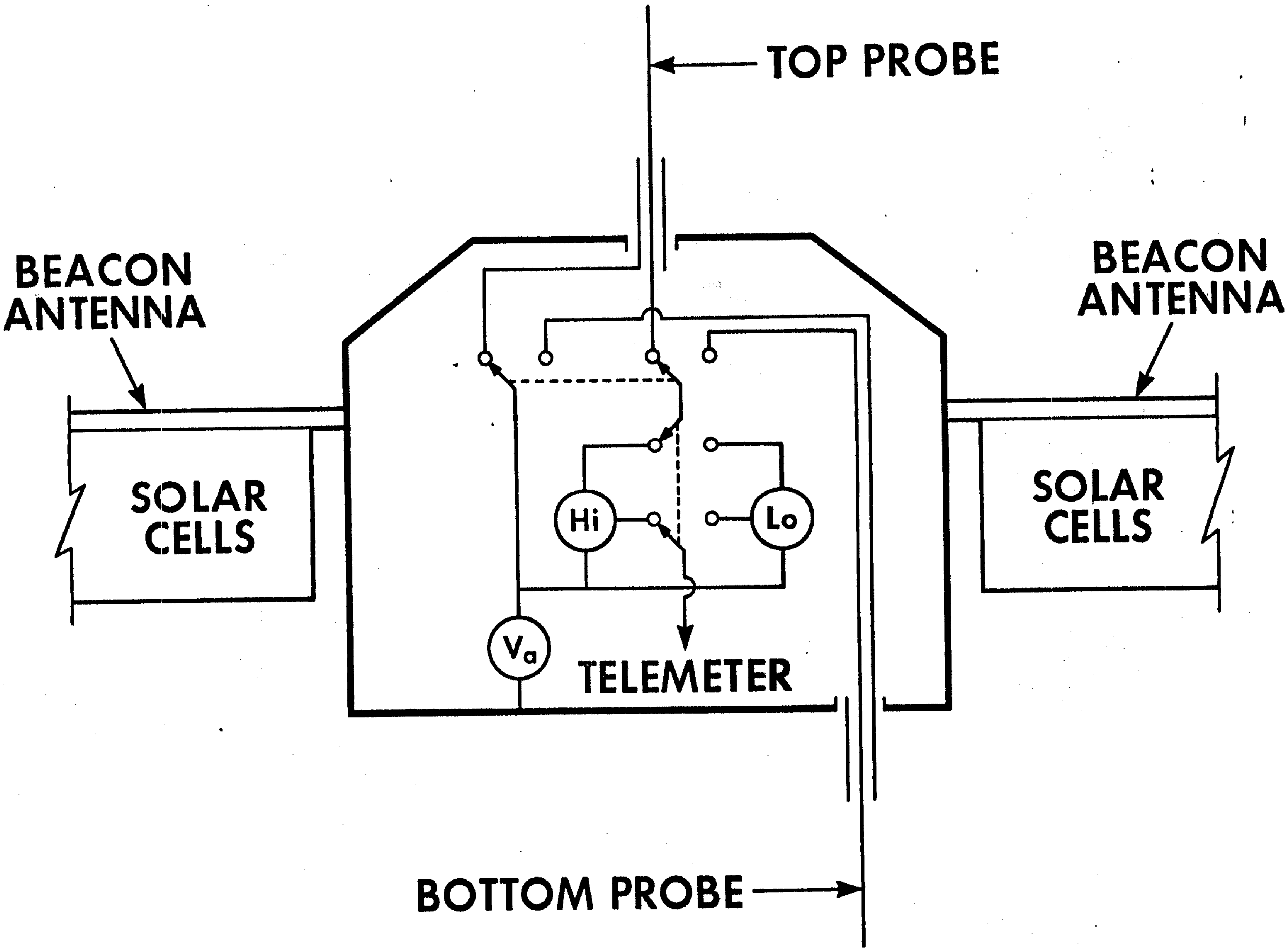

TOP PROBE
BEACON ANTENNA
BEACON ANTENNA
SOLAR CELLS
SOLAR CELLS
Hi
Lo
V_a
TELEMETER
BOTTOM PROBE

Fig. 1

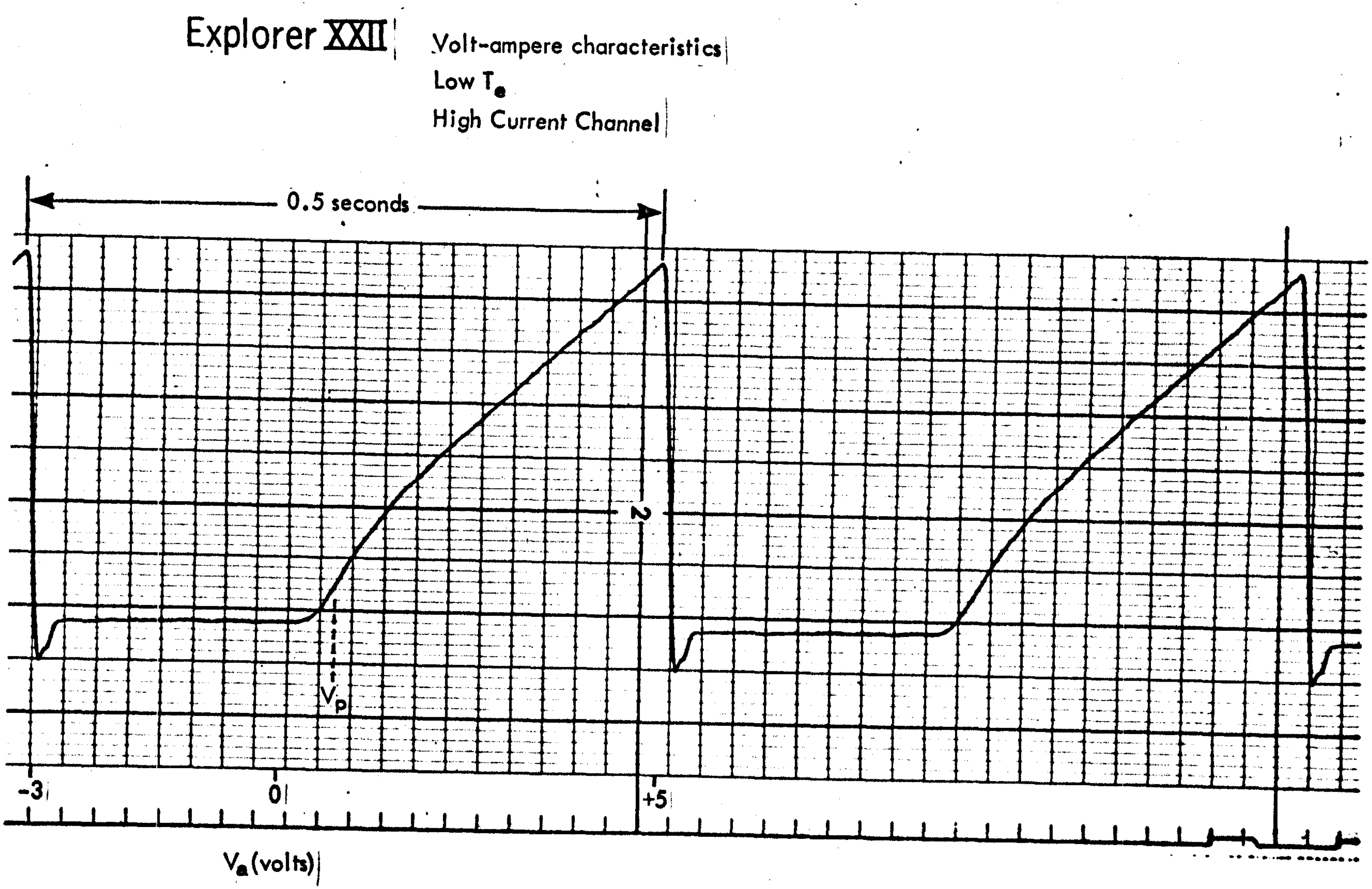

Explorer XXII
Volt-ampere characteristics
Low T_e
High Current Channel
0.5 seconds
2
V_p
-3
0
+5
V_a (volts)

Fig. 2

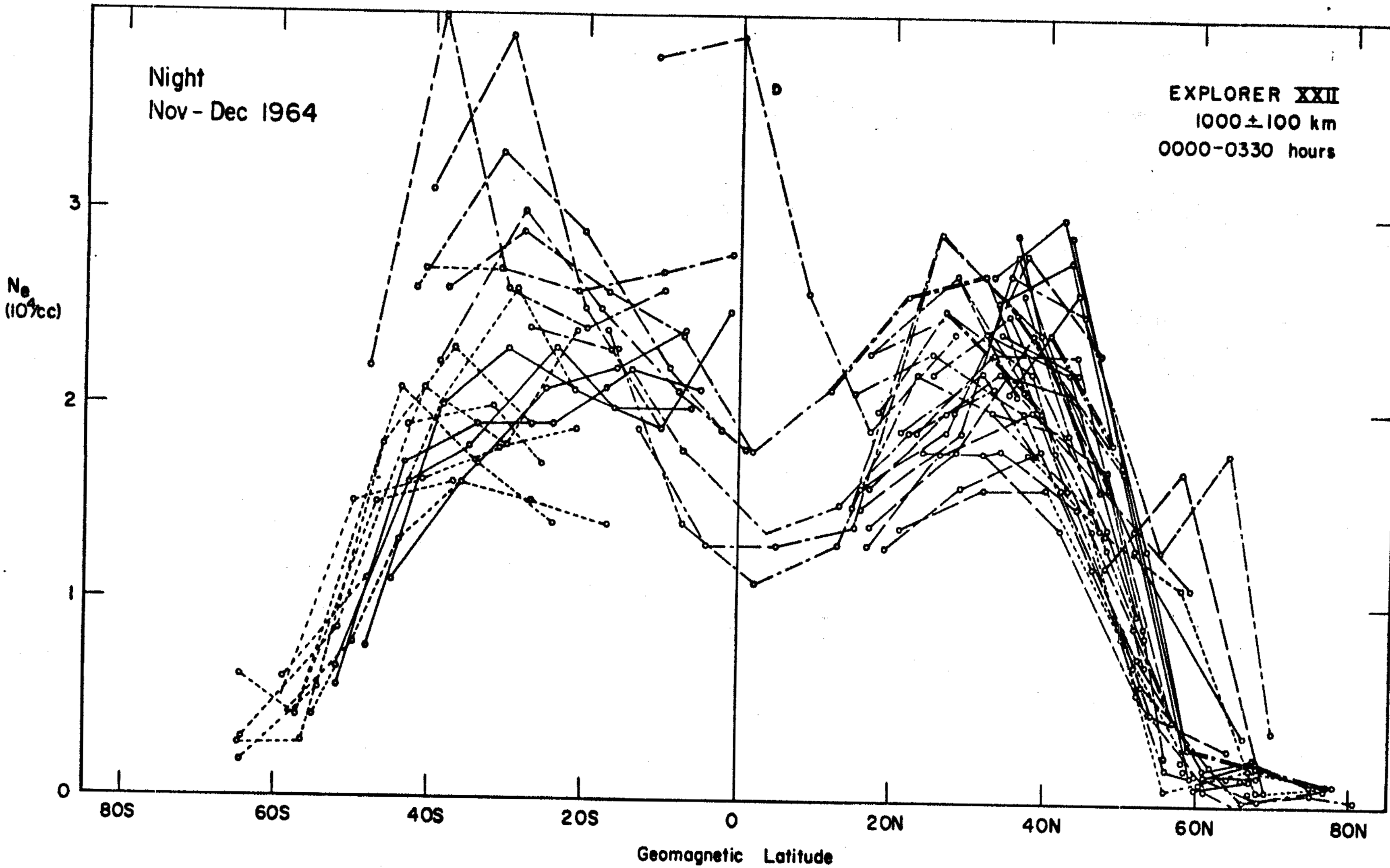
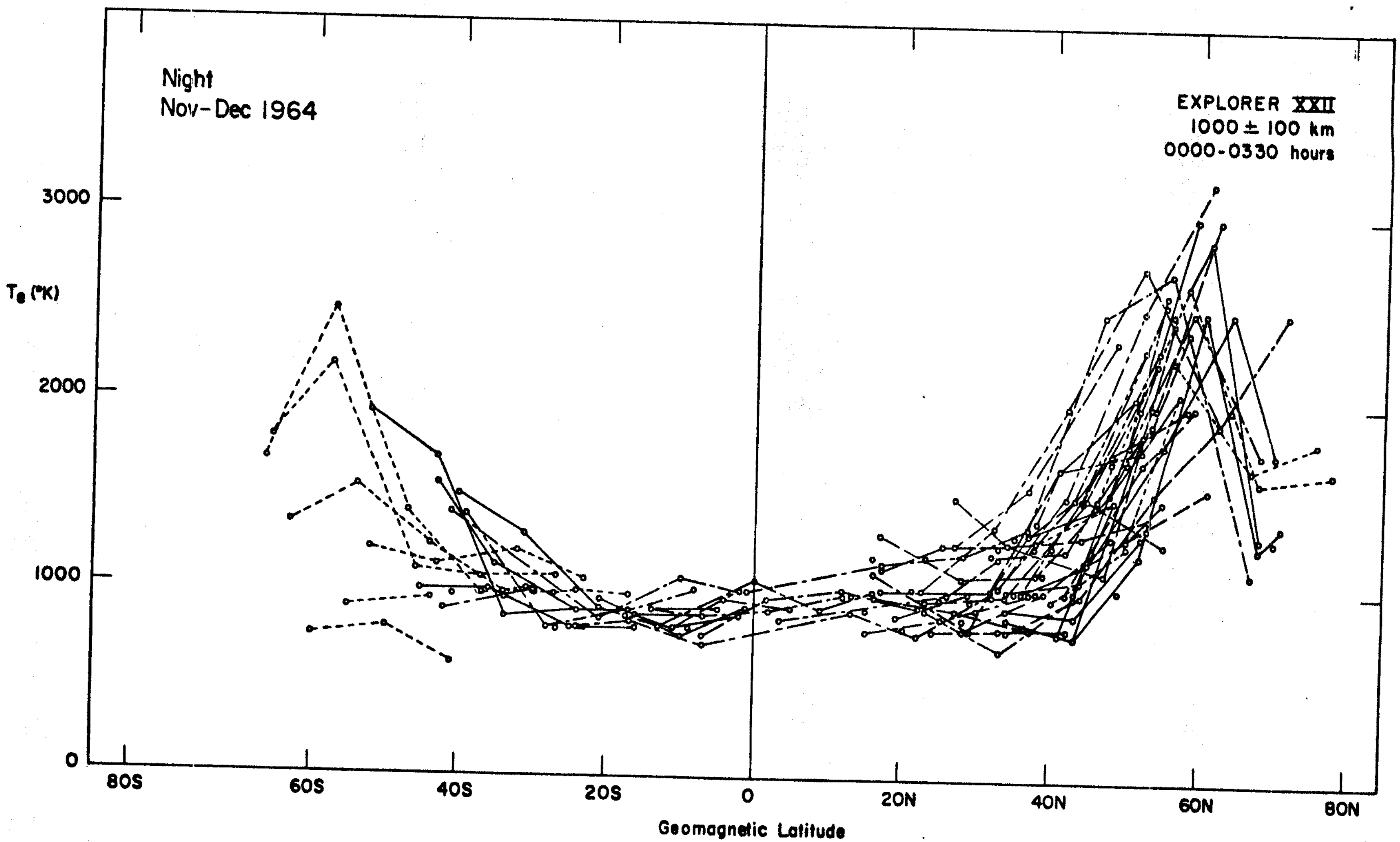
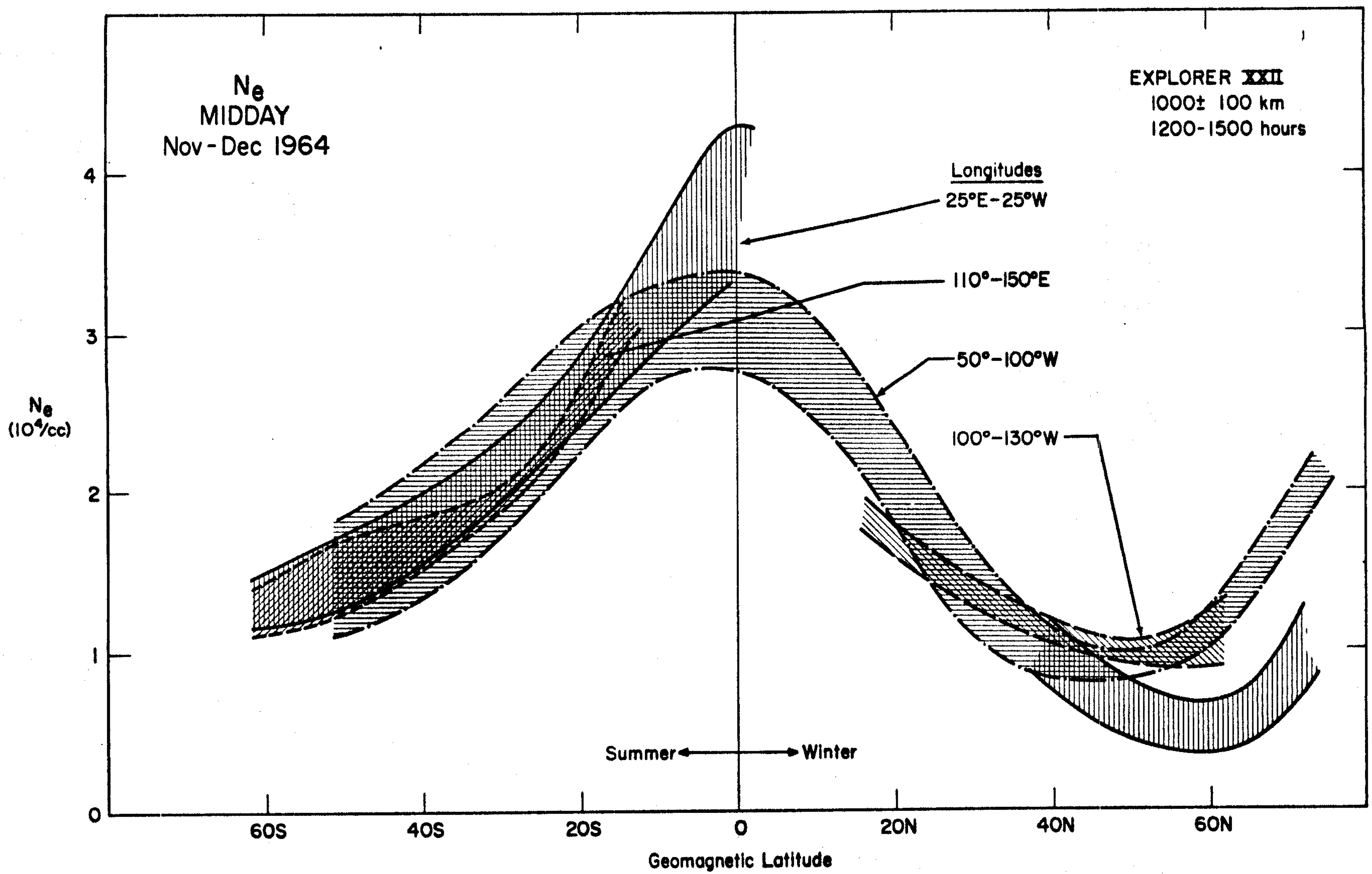

Night
Nov - Dec 1964
EXPLORER XXII
1000 ± 100 km
0000-0330 hours
D
N_e (10^4/cc)
0
1
2
3
80S
60S
40S
20S
0
20N
40N
60N
80N
Geomagnetic Latitude

Fig. 3



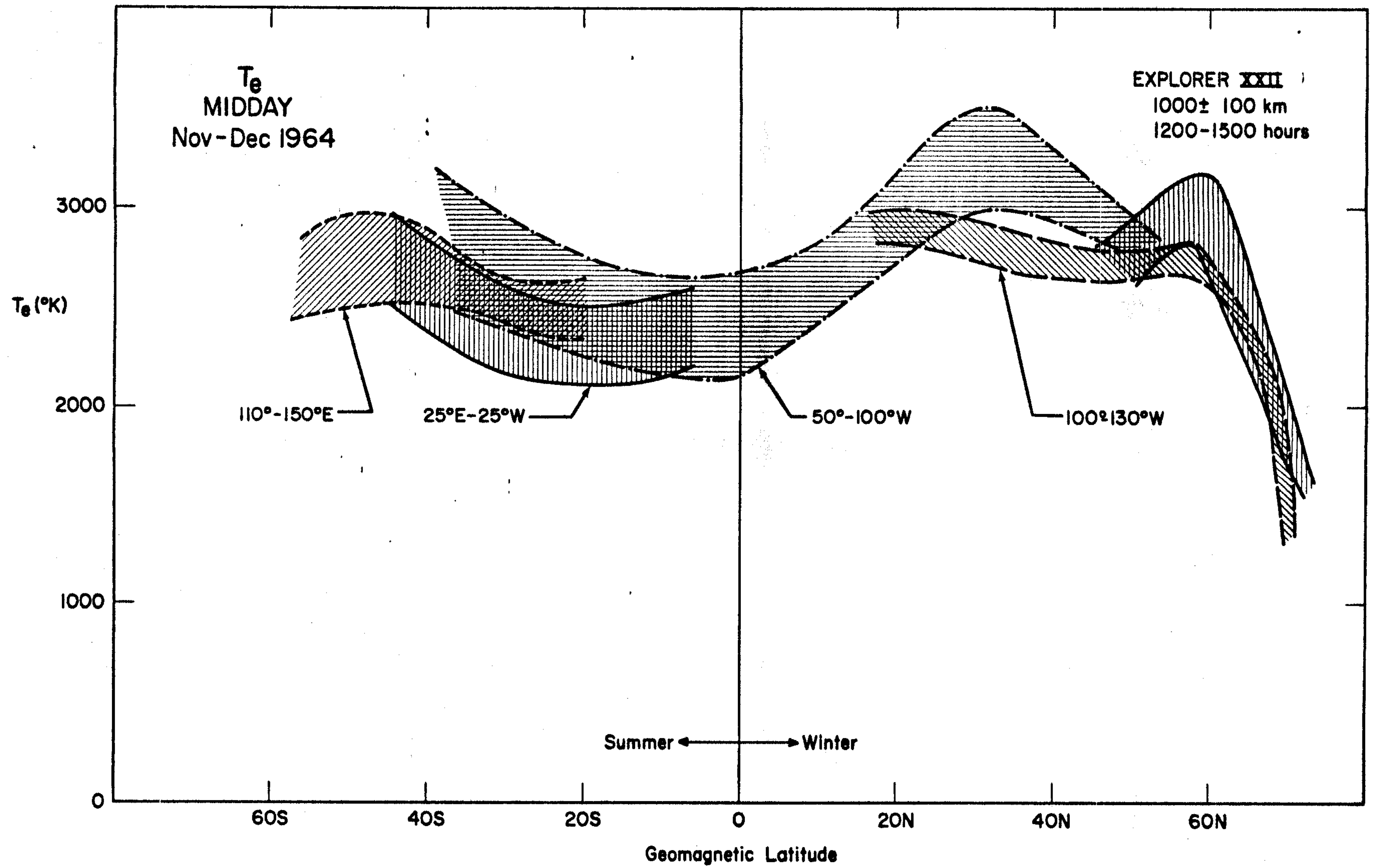
Night
Nov-Dec 1964
EXPLORER XXII
1000 ± 100 km
0000-0330 hours
T_e (°K)
3000
2000
1000
0
80S
60S
40S
20S
0
20N
40N
60N
80N
Geomagnetic Latitude

Fig. 4



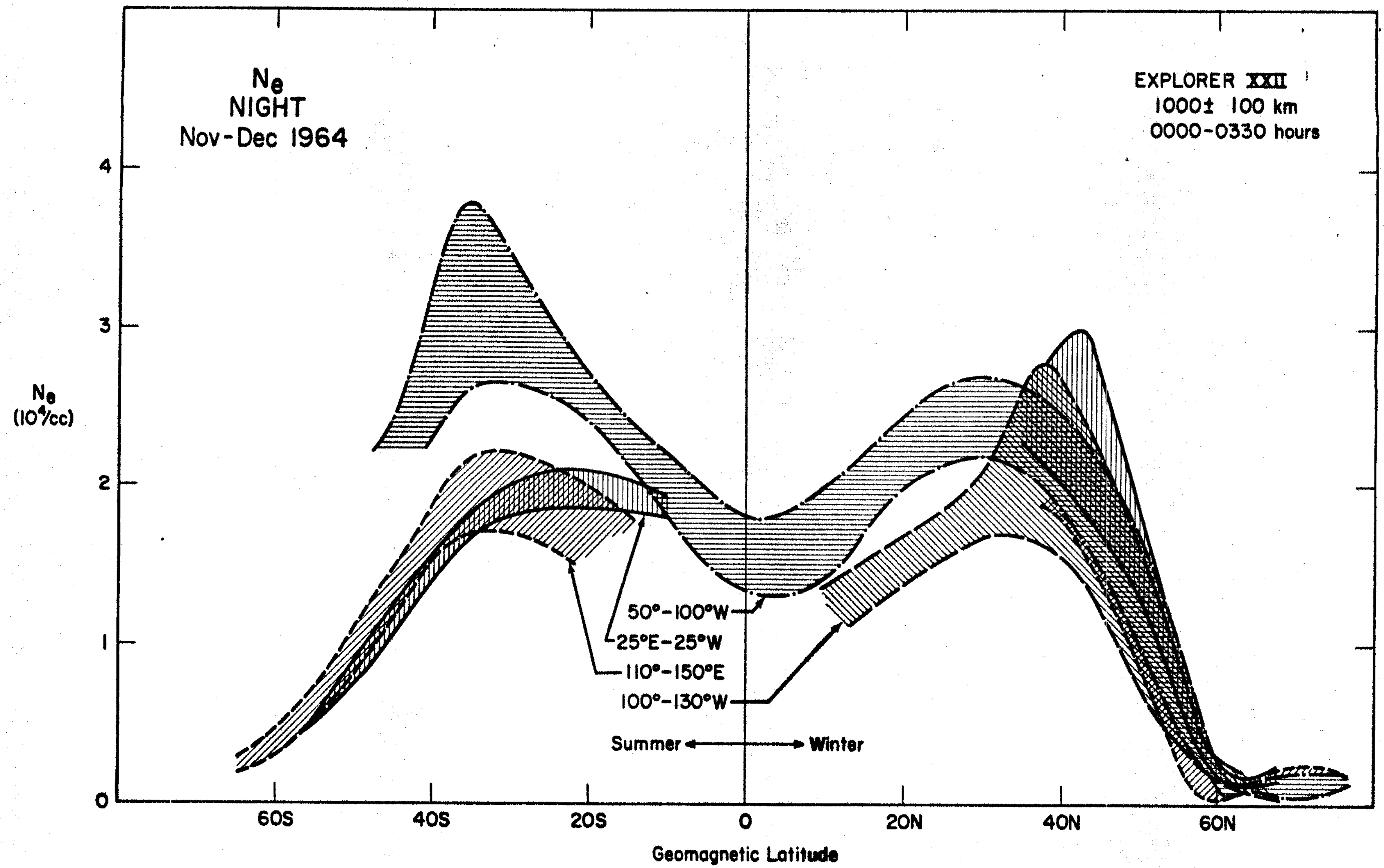
N_e
MIDDAY
Nov - Dec 1964
EXPLORER XXII
1000± 100 km
1200-1500 hours
Longitudes
25°E-25°W
110°-150°E
50°-100°W
100°-130°W
N_e
(10^4/cc)
0
1
2
3
4
Summer
Winter
60S
40S
20S
0
20N
40N
60N
Geomagnetic Latitude

Fig. 5



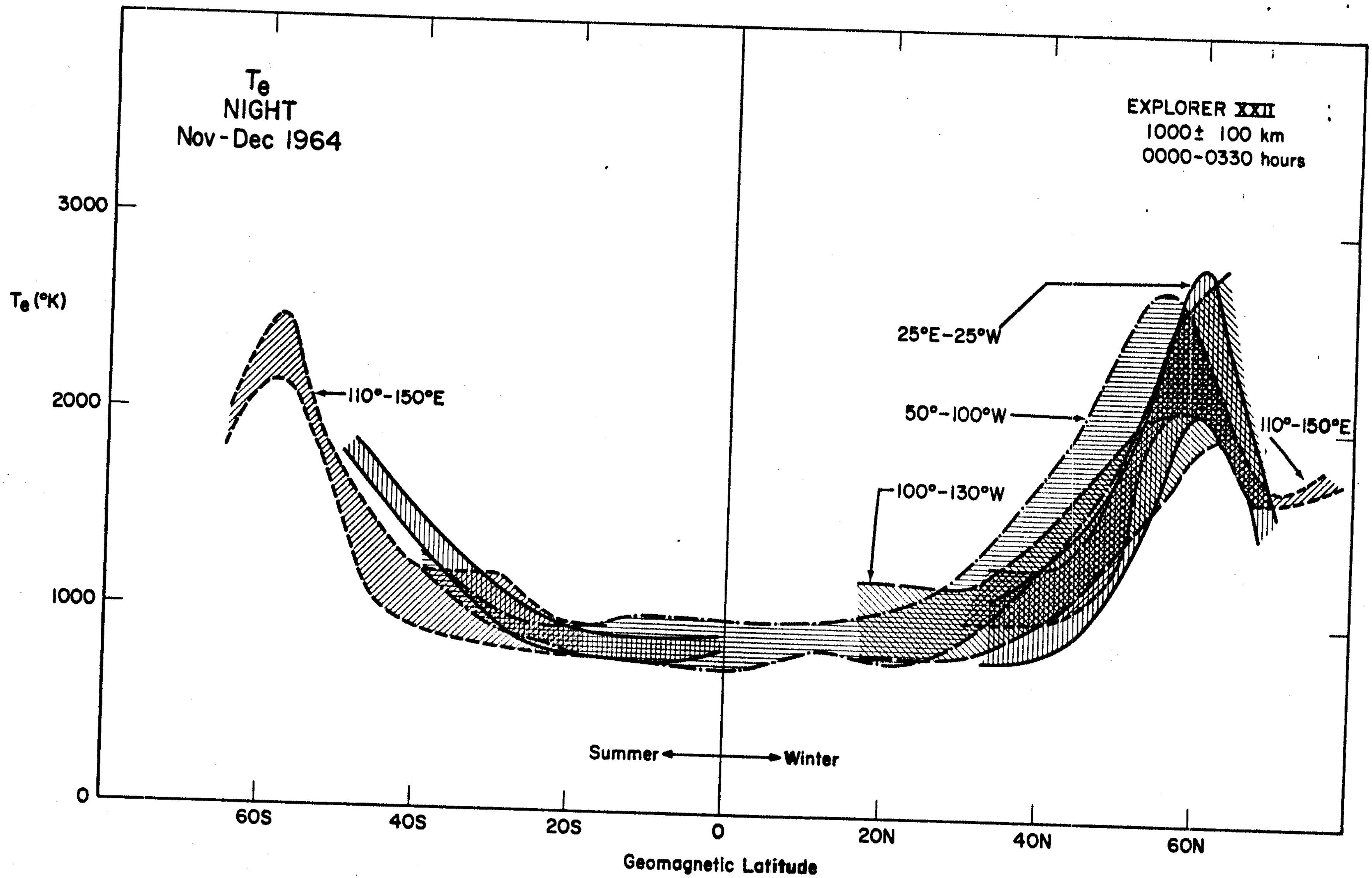
T_e
MIDDAY
Nov-Dec 1964
EXPLORER XXII
1000± 100 km
1200-1500 hours
3000
2000
1000
0
T_e (°K)
110°-150°E
25°E-25°W
50°-100°W
100°-130°W
Summer
Winter
60S
40S
20S
0
20N
40N
60N
Geomagnetic Latitude

Fig. 6



Ne
NIGHT
Nov-Dec 1964
EXPLORER XXII
1000± 100 km
0000-0330 hours
Ne
(10⁴/cc)
4
3
2
1
0
50°-100°W
25°E-25°W
110°-150°E
100°-130°W
Summer
Winter
60S
40S
20S
0
20N
40N
60N
Geomagnetic Latitude

Fig. 7



T_e
NIGHT
Nov-Dec 1964
EXPLORER XXII
1000± 100 km
0000-0330 hours
T_e (°K)
3000
2000
1000
0
110°-150°E
25°E-25°W
50°-100°W
100°-130°W
110°-150°E
Summer
Winter
60S
40S
20S
0
20N
40N
60N
Geomagnetic Latitude

Fig. 8

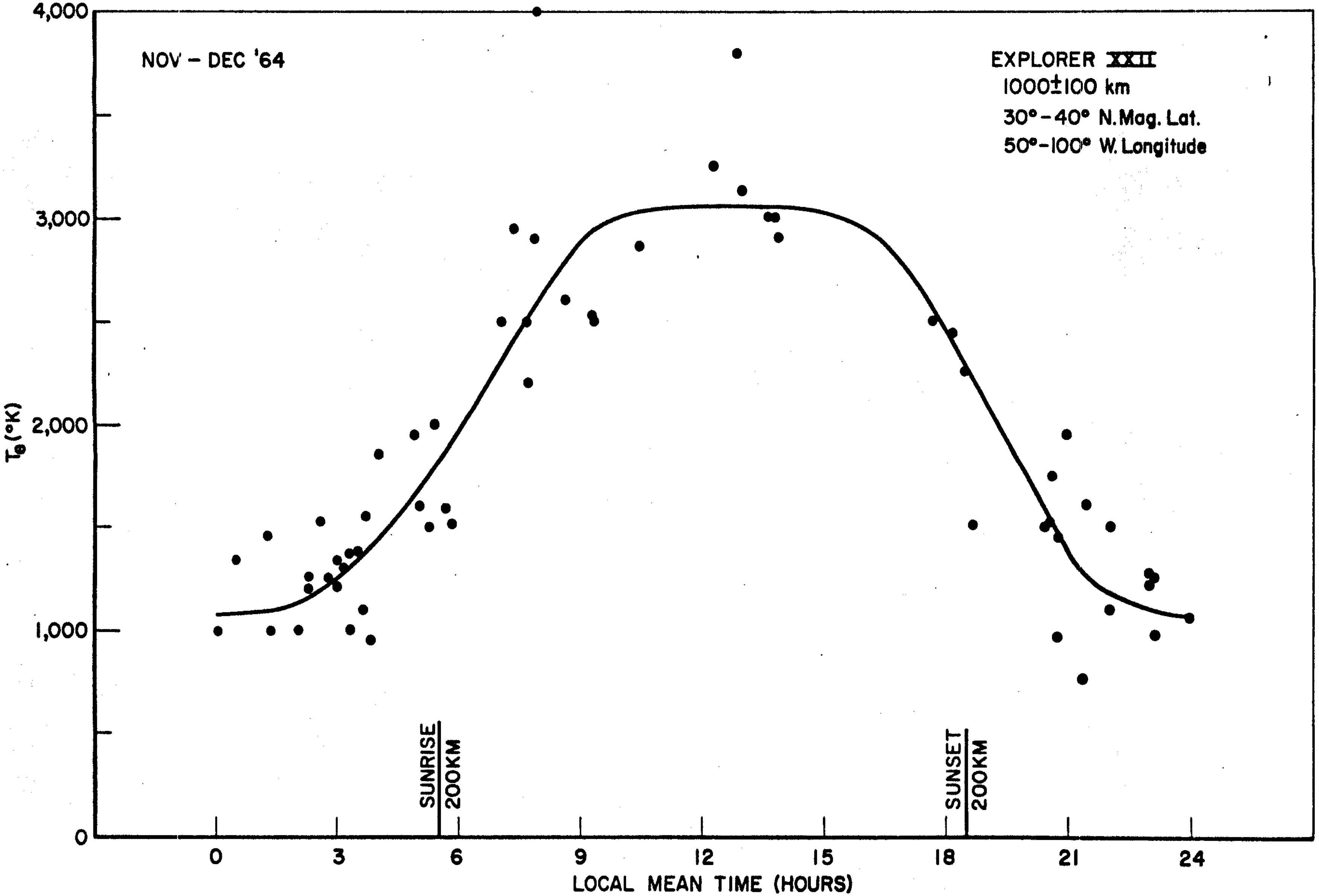
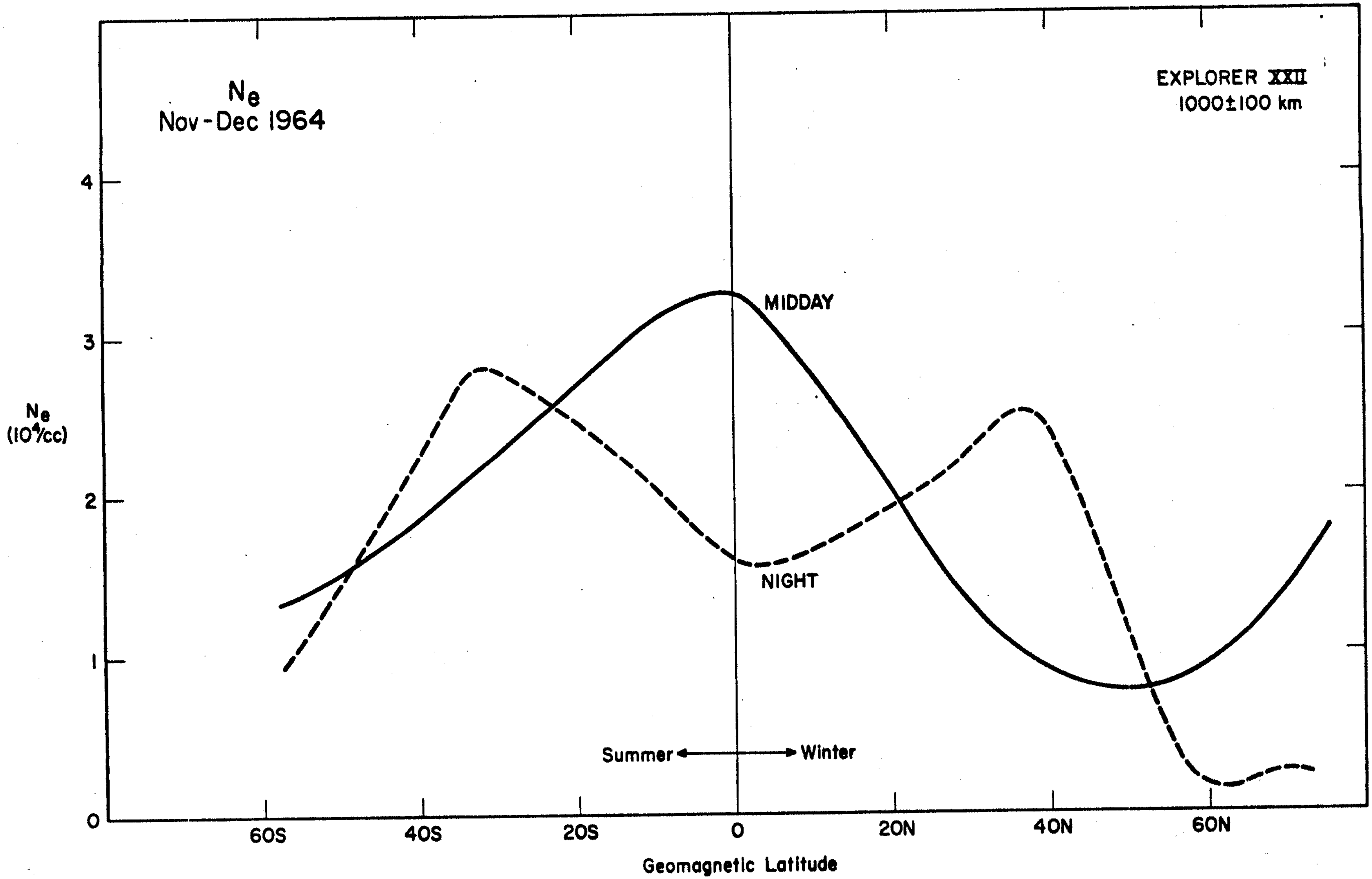
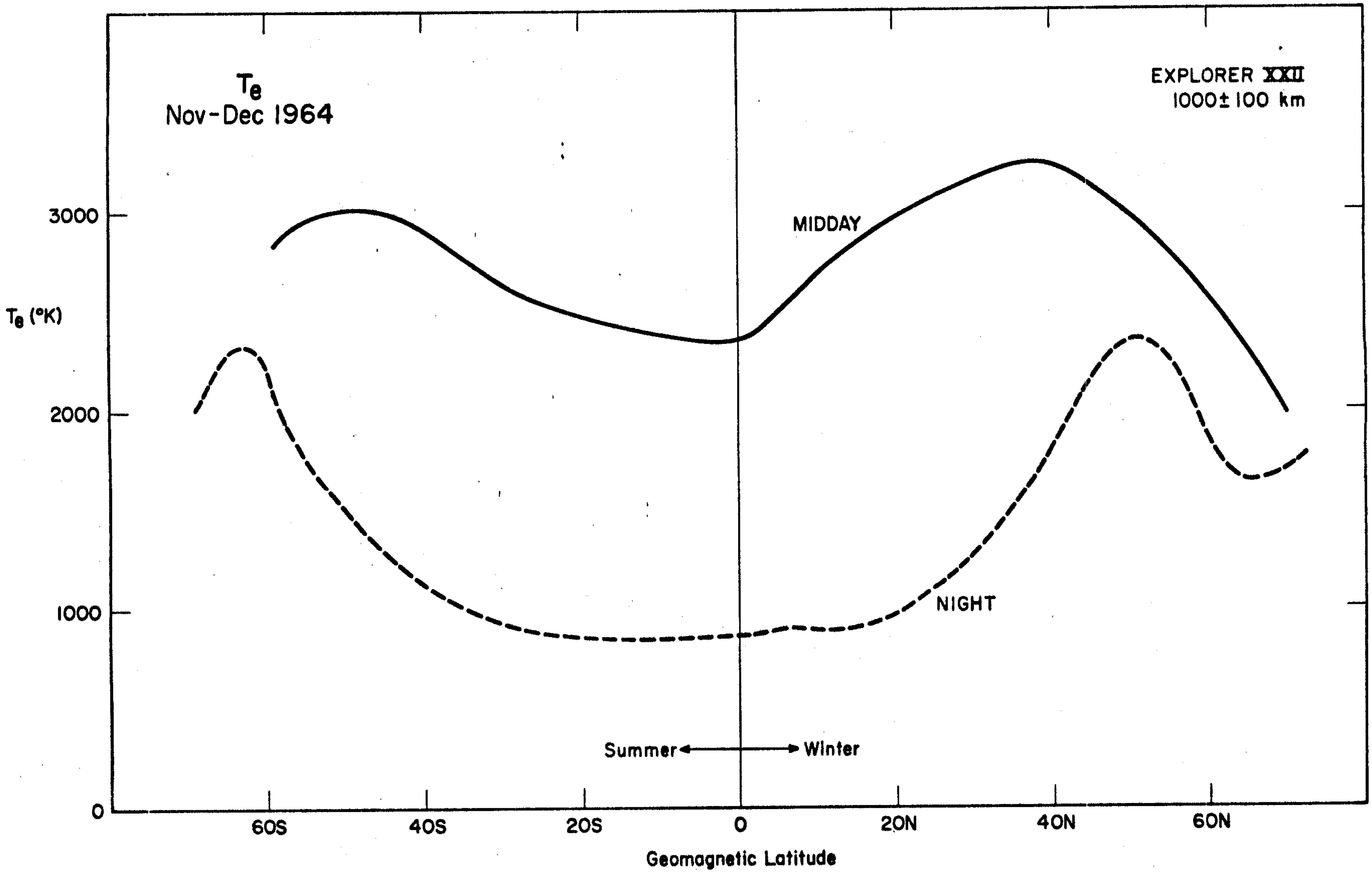

NOV - DEC '64
EXPLORER XXII
1000±100 km
30°-40° N.Mag. Lat.
50°-100° W. Longitude
4,000
3,000
2,000
1,000
0
T_e(°K)
SUNRISE
200KM
SUNSET
200KM
0
3
6
9
12
15
18
21
24
LOCAL MEAN TIME (HOURS)

Fig. 9



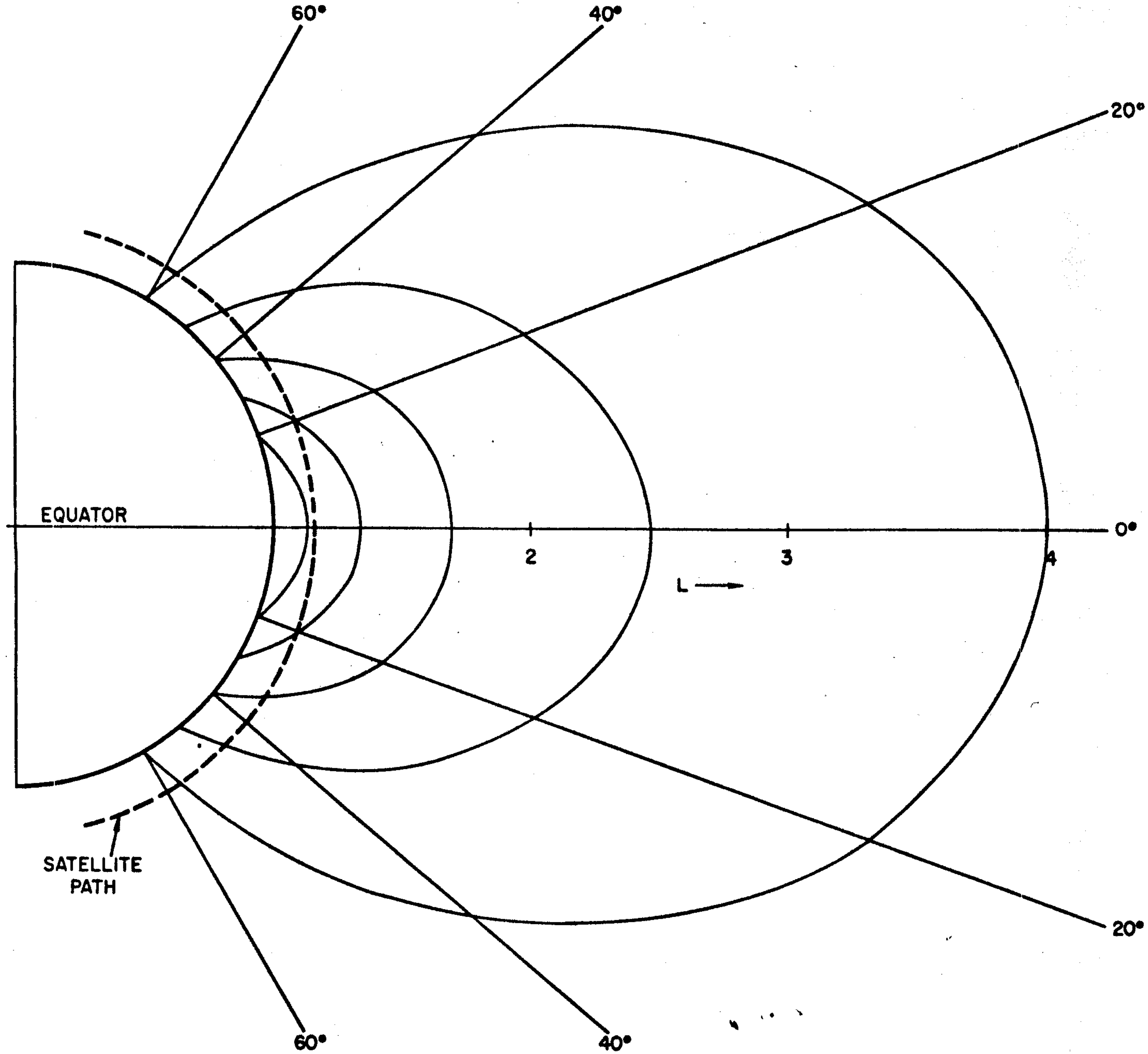
Ne
Nov-Dec 1964
EXPLORER XXII
1000±100 km
MIDDAY
NIGHT
Ne
(10⁴/cc)
4
3
2
1
0
60S
40S
20S
0
20N
40N
60N
Summer
Winter
Geomagnetic Latitude

Fig. 10



T_e
Nov-Dec 1964
EXPLORER XXII
1000± 100 km
MIDDAY
NIGHT
T_e (°K)
3000
2000
1000
0
Summer ←→ Winter
60S
40S
20S
0
20N
40N
60N
Geomagnetic Latitude

Fig. 11



EXPLORER XXII PATH IN THE PROTONOSPHERE.

Fig. 12